

# $\Lambda_c^+$ Production in Polarized $pp$ Scattering and Polarized Gluon Distribution

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## ABSTRACT

To extract information about the polarized gluon distribution,  $\Delta G(x, Q^2)$ , in the nucleons, we propose  $\Lambda_c^+$  productions in polarized  $pp$  scattering,  $p+\vec{p} \rightarrow \vec{\Lambda}_c^+ + X$ , which will be observed at RHIC experiment starting soon. For this process, we have calculated the spin correlation differential cross section,  $d\Delta\sigma/dp_T$ , and the spin correlation asymmetry defined by  $A_{LL} \equiv [d\Delta\sigma/dp_T]/[d\sigma/dp_T]$ . We have found that the  $A_{LL}$  is sensitive to the polarized gluon distribution in the nucleon and thus the process is promising for testing  $\Delta G(x, Q^2)$ .

PACS number(s): 13.88.+e, 14.20.Lg, 13.85.Ni

*To appear in Phys. Lett. B*

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The proton spin has long been considered to be given by the sum of the constituent quark spin,  $\Delta\Sigma$ , in the naive quark model, which suggests  $\Delta\Sigma = \Delta u + \Delta d = 1$  and  $\Delta s = 0$ , where  $\Delta u$ ,  $\Delta d$  and  $\Delta s$  denote the amount of the proton spin carried by  $u$ ,  $d$  and  $s$  quark, respectively. However, the experimental data on polarized structure function of nucleons,  $g_1^{p(n)}(x, Q^2)$ , have revealed that the contribution of the constituent quark spin to the proton spin is quite small,  $\Delta\Sigma \simeq 0.3$ , and the  $s$  quark is negatively polarized with a rather large value  $\Delta s \simeq -0.12$  [1]. This has been called the “proton spin puzzle” [2]. Actually, the proton spin is given by the sum of the spin of the quarks (valence and sea), gluons and the orbital angular momenta among them;

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_Z \rangle_{q+g}, \quad (1)$$

where  $\Delta G$  and  $\langle L_Z \rangle_{q+g}$  represent the amount of the proton spin carried by the gluon and the orbital angular momenta of quarks and gluons, respectively. To understand the physical ground of the sum rule of Eq.(1), it is important to know the behavior of the polarized partons in the nucleon. However, knowledge about the polarized gluon density,  $\Delta G(x, Q^2)$ , in a nucleon is still poor, though many processes have been proposed so far to extract information about it. On the other hand, the RHIC experiment which will start soon, will provide us many useful data for extracting information about polarized gluons in the near future.

In this paper, to extract the polarized gluon distribution  $\Delta G(x, Q^2)$ , we propose another process,  $p + \vec{p} \rightarrow \vec{\Lambda}_c^+ + X$  (Fig. 1), which would be observed in the forthcoming RHIC experiment. In this process,  $\Lambda_c^+$  is dominantly produced via fragmentation of a charm quark originated from gluon–gluon fusion. The reason we focus on this process is as follows. The  $\Lambda_c^+$  is composed of a heavy quark  $c$  and antisymmetrically combined light  $u$  and  $d$  quarks. Hence, the  $\Lambda_c^+$  spin is basically carried by a charm quark which is produced via gluon–gluon fusion at the lowest order in this process as shown in Fig. 2 <sup>#1</sup>. Therefore, observation of the spin of the produced  $\Lambda_c^+$  gives us information about the polarized gluons in the proton. In order to study this attractive process;

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<sup>#1</sup>Since charm quarks are not main constituents of the proton, the gluon–gluon fusion process is dominant for charm quark production.

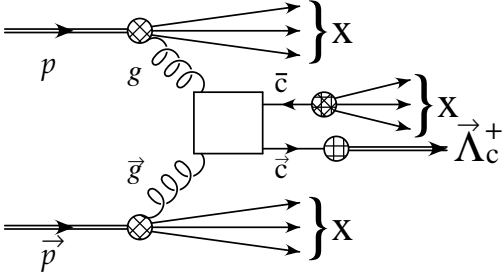


Figure 1: The diagram for  $p + \bar{p} \rightarrow \vec{\Lambda}_c^+ + X$  at the lowest order.

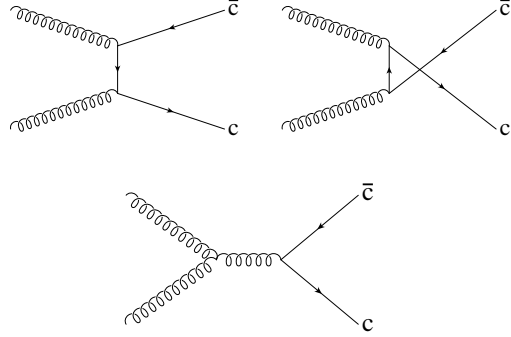


Figure 2: The subprocess at the lowest order.

$$p(p_A) + \bar{p}(p_B) \rightarrow \vec{\Lambda}_c^+(p_{\Lambda_c^+}) + X, \quad (2)$$

whose subprocess at the lowest order is

$$g(p_a) + \bar{g}(p_b) \rightarrow \bar{c}(p_c) + c(p_{\bar{c}}), \quad (3)$$

where  $p_i$  denotes the four-momenta of the  $i$ -particle<sup>#2</sup> and the over-arrow means that the particle polarization is either provided ( $g$ ) or measured ( $c$ ), we introduce two useful observables which will be measured by the forthcoming RHIC experiment: one is the spin correlation differential cross section,  $d\Delta\sigma/dp_T$ , and the other is the spin correlation asymmetry,  $A_{LL}$ . They are defined as follows;

$$\frac{d\Delta\sigma}{dp_T} \equiv \frac{d\sigma(++) - d\sigma(+-) + d\sigma(-- ) - d\sigma(-+)}{dp_T}, \quad (4)$$

$$A_{LL} \equiv \frac{[d\sigma(++) - d\sigma(+-) + d\sigma(-- ) - d\sigma(-+)]/dp_T}{[d\sigma(++) + d\sigma(+-) + d\sigma(-- ) + d\sigma(-+)]/dp_T}, \quad (5)$$

$$\equiv \frac{d\Delta\sigma/dp_T}{d\sigma/dp_T},$$

where  $d\sigma(+-)/dp_T$ , for example, denotes the spin-dependent differential cross section with the positive helicity of the target proton and the negative helicity of the produced  $\Lambda_c^+$ .

Let us consider the process in the proton-proton c.m. frame and take the four-momenta of  $p_i$  as follows;

$$p_{A,B} = \frac{\sqrt{s}}{2}(1, \pm\beta, \vec{0}) \quad \text{with} \quad \beta \equiv \sqrt{1 - \frac{4m_p^2}{s}},$$

<sup>#2</sup>For example, if  $i = \Lambda_c^+$ ,  $p_i$  indicates the four-momenta of  $\Lambda_c^+$ .

$$\begin{aligned}
p_{\Lambda_c^+} &= (E_{\Lambda_c^+}, p_L, \vec{p}_T) \\
&= (\sqrt{m_{\Lambda_c^+}^2 + p_T^2 \operatorname{cosec}^2 \Theta}, p_T \cot \Theta, \vec{p}_T), \\
p_{a,b} &= x_{a,b} p_{A,B} \quad , \quad p_c = \frac{p_{\Lambda_c^+}}{z},
\end{aligned} \tag{6}$$

where the first, second and third components in parentheses are the energy, the longitudinal momentum and the transverse momentum, respectively <sup>#3</sup>.  $\Theta$  and  $m_i$  represent the c.m. scattering angle of the produced  $\Lambda_c^+$  and mass of the  $i$ -particle, respectively.  $x_{a,b}$  and  $z$  are the momentum fraction of the proton carried by the gluon and the one of the charm quark carried by  $\Lambda_c^+$ , respectively. Notice that we assume that the scattering angle of the  $\Lambda_c^+$  produced in the final state and the angle of the charm quark in the subprocess are almost same,  $\theta_c \simeq \theta_{\Lambda_c^+} \equiv \Theta$ . This assumption is not unreasonable, because the momentum of  $\Lambda_c^+$  is almost carried by a charm quark whose mass is much larger than the other constituents of  $\Lambda_c^+$ . Then, using Eq.(6), we define the following Lorentz invariant variables;

$$\begin{aligned}
\tilde{s} &\equiv s - 2m_p^2, \\
\tilde{t} &\equiv t - m_p^2 - m_{\Lambda_c^+}^2 = -\sqrt{s} \left[ \sqrt{m_{\Lambda_c^+}^2 + p_T^2 \operatorname{cosec}^2 \Theta} + \beta p_T \cot \Theta \right], \\
\tilde{u} &\equiv u - m_p^2 - m_{\Lambda_c^+}^2 = -\sqrt{s} \left[ \sqrt{m_{\Lambda_c^+}^2 + p_T^2 \operatorname{cosec}^2 \Theta} - \beta p_T \cot \Theta \right],
\end{aligned} \tag{7}$$

where  $s$ ,  $t$  and  $u$  are conventional Mandelstam variables,  $s = (p_A + p_B)^2$ ,  $t = (p_{\Lambda_c^+} - p_B)^2$  and  $u = (p_{\Lambda_c^+} - p_A)^2$ , respectively. Furthermore, for the subprocess, we define

$$\hat{t}_1 \equiv \hat{t} - m_c^2 = \frac{x_b \tilde{t}}{z}, \quad \hat{u}_1 \equiv \hat{u} - m_c^2 = \frac{x_a \tilde{u}}{z}, \tag{8}$$

with the subprocess Mandelstam variables  $\hat{s} = (p_a + p_b)^2$ ,  $\hat{t} = (p_c - p_b)^2$  and  $\hat{u} = (p_c - p_a)^2$ .

Using Eq.(6)~Eq.(8), the spin correlation differential cross section(Eq.(4)) can be expressed as

$$\begin{aligned}
\frac{d\Delta\sigma}{dp_T} &= \int_{\Theta^{\min}}^{\Theta^{\max}} \int_{x_a^{\min}}^1 \int_{x_b^{\min}}^1 G_{p_A \rightarrow g_a}(x_a, Q^2) \Delta G_{\vec{p}_B \rightarrow \vec{g}_b}(x_b, Q^2) \Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}(z) \\
&\quad \times \frac{d\Delta\hat{\sigma}}{d\hat{t}} J dx_a dx_b d\Theta,
\end{aligned} \tag{9}$$

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<sup>#3</sup>Here we do not neglect the masses of all particles, though we basically follows the method of Ref. [3].

where  $G_{p_A \rightarrow g_a}(x_a, Q^2)$ ,  $\Delta G_{\vec{p}_B \rightarrow \vec{g}_b}(x_b, Q^2)$  and  $\Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}(z)$  represent the unpolarized gluon distribution function, the polarized gluon distribution function and the spin-dependent fragmentation function of the outgoing charm quark decaying into a polarized  $\vec{\Lambda}_c^+$ , respectively. Moreover  $J$  is the Jacobian which transform the variables  $z$  and  $\hat{t}$  into  $\Theta$  and  $p_T$ . Unfortunately, at present there is no established spin-dependent fragmentation functions because of lack of experimental data. However, since a charm quark is much heavier than other constituents of  $\Lambda_c^+$ , it is expected to be very rare for a charm quark to change its spin alignment during fragmentation process. Therefore, it is not unreasonable to substitute  $D_{c \rightarrow \Lambda_c^+}$  for  $\Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}$ . In this work, we use the model by Peterson et al. [4] for both  $D_{c \rightarrow \Lambda_c^+}$  and  $\Delta D_{\vec{c} \rightarrow \vec{\Lambda}_c^+}$ <sup>#4</sup>. For the subprocess, the spin correlation differential cross section,  $d\Delta\hat{\sigma}/d\hat{t}$  is calculated to be

$$\frac{d\Delta\hat{\sigma}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}} \left[ \frac{m_c^2}{24} \left\{ \frac{9\hat{t}_1 - 19\hat{u}_1}{\hat{t}_1\hat{u}_1} + \frac{8\hat{s}}{\hat{u}_1^2} \right\} + \frac{\hat{s}}{6} \left\{ \frac{\hat{t}_1 - \hat{u}_1}{\hat{t}_1\hat{u}_1} \right\} - \frac{3}{8} \left\{ \frac{2\hat{t}_1}{\hat{s}} + 1 \right\} \right] \quad (10)$$

and the Jacobian,  $J$ , is given by

$$J = \frac{2s\beta p_T^2 \text{cosec}^2\Theta}{z\tilde{s}\sqrt{m_{\Lambda_c^+}^2 + p_T^2 \text{cosec}^2\Theta}}. \quad (11)$$

where  $z$  is

$$z = \frac{x_1}{x_a} + \frac{x_2}{x_b} \quad (12)$$

with  $x_1 = -\tilde{t}/\tilde{s}$  and  $x_2 = -\tilde{u}/\tilde{s}$ . The minimum of  $x_a$ ,  $x_b$  are given by

$$x_a^{\min} = \frac{x_1}{1 - x_2}, \quad x_b^{\min} = \frac{x_a x_2}{x_a - x_1}. \quad (13)$$

The unpolarized differential cross sections were calculated by Babcock et al. [5].

For numerical calculation, we use as input parameters,  $m_c = 1.5$  GeV,  $m_p = 0.938$  GeV and  $m_{\Lambda_c^+} = 2.28$  GeV [6]. We limit the integration region of  $\Theta$  and  $p_T$  of produced  $\Lambda_c^+$  as  $\frac{\pi}{6} \leq \Theta \leq \frac{5\pi}{6}$  and  $3 \text{ GeV} \leq p_T \leq 20 \text{ GeV}$  for  $\sqrt{s} = 200$  GeV and 500 GeV, in order to get rid of the contribution of the diffractive  $\Lambda_c^+$  production and also the  $\Lambda_c^+$  production through a single charm quark production via  $W$  boson exchange and  $W$  boson production. As for the gluon distributions,

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<sup>#4</sup> Actually, we used the Peterson functional form presented by the Particle Data Group [6], which is normalized as  $\int D_{c \rightarrow \Lambda_c^+}(z) dz = 0.503$ .

we take the GS96(set-A and -B) [7] and the GRSV96 [8] parameterization models for the polarized gluon distribution function and the GRV95 [9] model for the unpolarized one. Note that the GS96 and GRSV96 models can excellently reproduce experimental results for the polarized structure function of nucleons, though behavior of these polarized gluon distributions is quite different. In other words, the data on polarized structure functions of nucleons and deuteron alone are not enough to distinguish the model of gluon distribution functions. We are interested in the sensitivity of those observables of Eq.(4) and Eq.(5) on the polarized gluon distributions in the nucleon in this process.

We show the  $p_T$  distribution of  $d\Delta\sigma/dp_T$  and  $A_{LL}$  in Fig. 3 for  $\sqrt{s} = 200$  GeV and in Fig. 4 for  $\sqrt{s} = 500$  GeV, respectively. Notice that in Fig. 4 the absolute value of  $d\Delta\sigma/dp_T$  is presented, since the negative value of  $d\Delta\sigma/dp_T$  cannot be depicted in the figure which has an ordinate with logarithmic scale. Actually, for the case of  $\sqrt{s} = 500$  GeV, the value of  $d\Delta\sigma/dp_T$  becomes negative for  $p_T$  smaller than the value corresponding to the sharp dip shown in Fig. 4. On the other hand,  $d\Delta\sigma/dp_T$  at  $\sqrt{s} = 200$  GeV is positive for all  $p_T$  regions as shown in Fig. 3. To understand this quite different behavior of  $d\Delta\sigma/dp_T$  depending on  $\sqrt{s}$ , some comments are in order. As seen from Eq.(9)~Eq.(13), the sign of  $d\Delta\sigma/dp_T$  is determined by the sign of  $d\Delta\hat{\sigma}/d\hat{t}$  because all variables except for  $d\Delta\hat{\sigma}/d\hat{t}$  are positive in whole kinematical regions of  $x_a$ ,  $x_b$  and  $\Theta$ . Since both  $\hat{t}_1$  and  $\hat{u}_1$  are negative and smaller than  $\hat{s}$  in magnitude, the sign of  $d\Delta\hat{\sigma}/d\hat{t}$  mainly originates from the second term of the right hand side of Eq.(10), in which  $\hat{t}_1 - \hat{u}_1$  is calculated to be

$$\hat{t}_1 - \hat{u}_1 \simeq x_b\sqrt{s} \left\{ x_a\sqrt{s} - \frac{2}{z} \left( \sqrt{m_{\Lambda_c^+}^2 + p_T^2 \text{cosec}^2\Theta} + p_T \cot \Theta \right) \right\}, \quad (14)$$

in the limit of the massless proton <sup>#5</sup>. Furthermore, in the same limit,  $x_a^{\min}$  reduces to

$$x_a^{\min} \simeq \frac{\sqrt{m_{\Lambda_c^+}^2 + p_T^2 \text{cosec}^2\Theta} + p_T \cot \Theta}{\sqrt{s} - \left( \sqrt{m_{\Lambda_c^+}^2 + p_T^2 \text{cosec}^2\Theta} - p_T \cot \Theta \right)} \quad (15)$$

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<sup>#5</sup>In the region of  $s$  much larger than  $m_p^2$  where we are now focusing, this limit with  $s = \tilde{s}$  and  $\beta = 1$  is a good approximation.

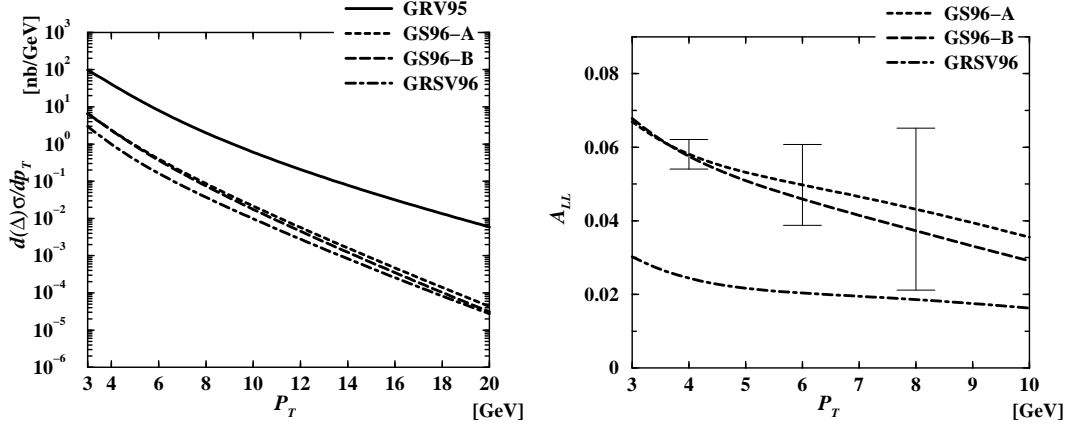


Figure 3: The unpolarized and spin correlation differential cross section (left panel) and the spin correlation asymmetry (right panel) as a function of  $p_T$  at  $\sqrt{s} = 200$  GeV. The solid line in the left figure represents the unpolarized differential cross section with the GRV95 model for the unpolarized gluon distribution. The dashed, long-dashed and dot-dashed lines indicate numerical results with the set A, B of the GS96 model and the GRSV96 model, respectively, for the polarized gluon distribution. The error bars for the dashed line shows the statistical sensitivity (see text).

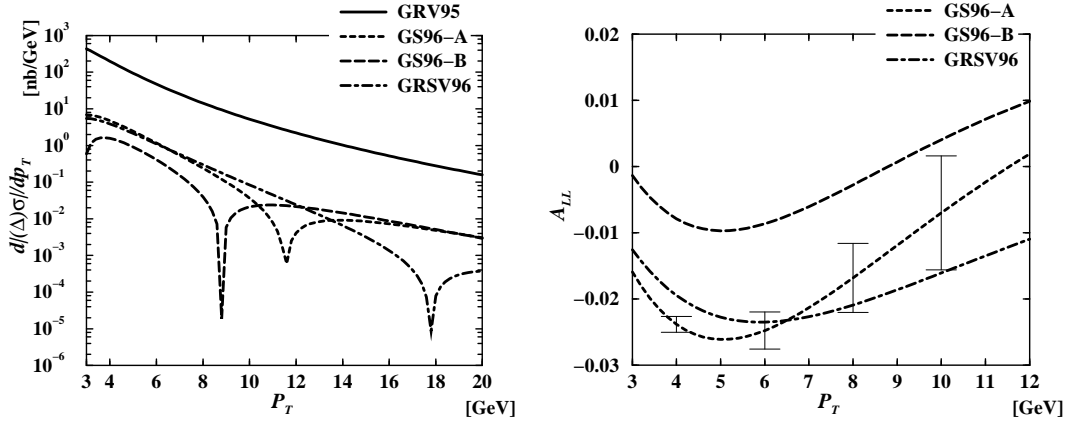


Figure 4: The same as in Fig. 3, but for  $\sqrt{s} = 500$  GeV.

from Eq.(13). Eq.(15) shows that  $x_a$  becomes very small in some region of  $p_T$  and  $\Theta$  when  $\sqrt{s}$  is large and hence leads to large values of the gluon distributions,  $G_{p_A \rightarrow g_a}(x_a, Q^2)$ . Thus when Eq.(14) becomes negative due to very small  $x_a$ , the negative contribution of  $d\Delta\hat{\sigma}/d\hat{t}$  to  $d\Delta\sigma/dp_T$  becomes larger for  $\sqrt{s} = 500$  GeV than for  $\sqrt{s} = 200$  GeV because  $G_{p_A \rightarrow g_a}(x_a, Q^2)$  is larger at smaller  $x_a$ . Therefore, for large  $\sqrt{s}$  such as  $\sqrt{s} = 500$  GeV, even after integration,  $d\Delta\sigma/dp_T$  is negative for  $p_T$  smaller than the value corresponding to the dip, as shown in Fig. 4. It is very interesting to note that the behavior of  $A_{LL}$  strongly depends on  $\sqrt{s}$  as shown

from Figs. 3 and 4. In any case, both figures show that  $A_{LL}$  is sensitive to the polarized gluon distribution function.

Finally, to examine if our predictions can be tested at the forthcoming RHIC experiment, we estimate the statistical sensitivity of the spin correlation asymmetry,  $\delta A_{LL}$ , according to the method given in Ref[10]. The value of  $\delta A_{LL}$  is estimated by

$$\delta A_{LL} \simeq \frac{1}{P} \frac{1}{\sqrt{b_{\Lambda_c^+} \varepsilon \mathcal{L} T \sigma}}. \quad (16)$$

We can estimate the statistical sensitivity,  $\delta A_{LL}$ , for  $T=100$ -day experiments by using the parameters of the beam polarization ( $P = 70\%$ ), a luminosity ( $\mathcal{L} = 8 \times 10^{31} \text{ (} 2 \times 10^{32} \text{) cm}^{-2}\text{sec}^{-1}$  for  $\sqrt{s} = 200 \text{ (} 500 \text{) GeV}$ ), the trigger efficiency ( $\varepsilon \equiv 10\%$ ) of detecting high  $p_T$  charm production events through their semi-leptonic decays and a branching ratio ( $b_{\Lambda_c^+} \equiv Br(\Lambda_c^+ \rightarrow pK^-\pi^+) \simeq 5\%$  [6])<sup>#6</sup>.  $\sigma$  denotes the unpolarized cross section integrated over suitable  $p_T$  region. The results are summarized in the right panels of Figs. 3 and 4. As shown in these figures,  $\delta A_{LL}$  is smaller than the difference of the model predictions at moderate  $p_T$  region and thus our predictions are expected to be tested in the RHIC experiment, though the differential cross section,  $d\sigma/dp_T$ , becomes rapidly smaller with increasing  $p_T$ , and thus in the larger  $p_T$  region,  $\delta A_{LL}$  becomes too large to distinguish the model of polarized gluon distribution functions. Furthermore, note that  $\delta A_{LL}$  is expected to become small if a trigger efficiency  $\varepsilon$  is improved and/or another decay modes of  $\Lambda_c^+$  are additionally taken into account. Moreover, the statistics should be twice by using the  $\overline{\Lambda}_c^+$  data as well, since high  $p_T$  charm production is dominated by gluon fusion, as long as the  $\Lambda_c^+$  decays satisfy  $CP$  invariance.

In summary, to extract the polarized gluon distribution  $\Delta G(x, Q^2)$ , we proposed a new polarized process,  $p + \vec{p} \rightarrow \vec{\Lambda}_c^+ + X$ , which could be observed in the forthcoming RHIC experiment. We calculated the the spin correlation differential cross section,  $d\Delta\sigma/dp_T$ , and the spin correlation asymmetry,  $A_{LL}$ , and found that  $A_{LL}$  is quite sensitive to the polarized gluon distribution functions; we can rather

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<sup>#6</sup>Here, we simply assumed the efficiency for reconstructing the  $pK^-\pi^+$  decay of  $\Lambda_c^+$  to be 100 % by quoting only the decay branching fraction. Although the actual efficiency might be more likely to be less than 10 - 20 % rather than more than 50 % (almost perfect, background free measurement), this should be studied by experimentalists in the forthcoming RHIC experiment.



clearly distinguish the model of polarized gluon distribution functions at moderate  $p_T$  region. It is also remarkable that the  $A_{LL}$  shows very different behavior in the region of  $\sqrt{s} = 200 \sim 500$  GeV, covered by RHIC. Therefore, the process looks promising for testing the model of polarized gluon distribution functions, though the present analysis is based on the leading order calculation. In order to get more profound information on the behavior of polarized gluons, we need the next-to-leading order calculation. Furthermore, we also need further investigation of the polarized fragmentation functions,  $\Delta D_{\tilde{c} \rightarrow \tilde{\Lambda}_c^+}(z)$ , to get more reliable prediction. Although these subjects are interesting and important in their own right, they are out of scope in this work.

We hope our prediction will be tested in the forthcoming RHIC experiment.

One of the authors (T.M.) would like to thank for the financial support by the Grant-in-Aid for Scientific Research, Ministry of Education, Science and Culture, Japan (No.11694081).

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